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REPORT NO. 215-5

PREPARED FOR:

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DIRECTOR, ENGINEERING PSYCHOLOGY PROGRAM
PSYCHOLOGICAL SCIENCES DIVISION
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
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This is a report of work accomplished on one task in the project entitled, Operational Decision Aids (ODA), which was initiated in 1974 by the Office of Naval Research to develop aids for Navy command and control functions and make them available for incorporation in the design of future systems. The decision aids developed by ONR contractors under the ODA program make heavy use of interactive graphics. It was felt that knowledge about other military use of interactive graphics would enable us to evaluate and improve → over

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upon our own techniques as we are developing them. Therefore the authors looked for and found three decision aids that are being developed under sponsorship of agencies other than ONR and that have the following characteristics:

1. The solution process performed by the system consisting of an operator, hardware, and software considers many interacting variables;
2. The operator's role is to structure the problem and/or guide the process through multiple steps to a solution satisfactory to him;
3. The system uses interactive graphics to represent the problem and to display potential solutions; and
4. The problem is dynamic and the system helps the operator to consider problem dynamics.

The report describes these three aids.

As a separate matter, a comparison was made between the performance of two nonlinear programming algorithms that can be used to find the best path through a field of enemy sensors for an air strike. One of the algorithms uses a sophisticated gradient search approach to find a local optimum. The other uses a simple non-gradient approach. Surprisingly, the gradient search algorithm was found to be less efficient than the non-gradient algorithm. The most likely explanation is that gradient algorithms using approximation methods to find derivatives do not work well at the low precision required for competition with the non-gradient algorithm in the air strike problem. The chain of reasoning leading to this conclusion is given in the report.

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AN INVESTIGATION OF SELECTED
ALTERNATIVE DECISION AIDS

Report No. 215-5

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Prepared for:

Code 455
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EXECUTIVE BRIEF

This is the fourth technical report by Integrated Sciences Corporation (ISC) as one of a group of contractors working on the Operational Decision Aids (ODA) program directed by the Office of Naval Research. The ODA program was initiated in 1974. It is intended to develop a variety of decision aids and test and evaluate their usefulness to the Navy. Although the program is not tied to any specific command and control hardware system, it has focused on the functions of a Task Force Commander (TFC) and his staff. The role of ISC has been to find ways to improve man-machine communication by allocating functions between man and machine that take advantage of their respective strengths.

The decision aids developed by ONR contractors under the ODA program make heavy use of interactive graphics. It was felt that knowledge about other military use of interactive graphics would enable us to evaluate and perhaps improve upon our own techniques as we are developing them. ISC therefore looked for other decision aids that make heavy use of interactive graphics and are being developed under sponsorship of agencies other than ONR.

ISC inquiries found two such aids. One of these, Calspan Corporation's Defense Analysis System (DAS), treats the same problem as ISC's Operator Aided Optimization (OAO) aids, namely, finding a route for an air strike through enemy defenses. There are significant differences between Calspan's DAS and the ISC aids that prevent a straightforward comparison between them. Some of these differences are named in Subsection 2.2.8 of the report

DAS incorporates two techniques that are worth considering for inclusion in future aids that might be designed for the ODA program. One is a modified version of the standard dynamic programming algorithm that speeds the solution process. The other technique is calculation and display of a corridor of grid points around an optimum path through enemy defenses. Any path within the corridor is less than optimal but the degree of suboptimality is not greater than an operator-specified percentage. The operator can use the corridor display as a basis for smoothing the computer calculated optimum. Smoothing is done to make the speed, altitude, and course changes more feasible than the

sharp changes that are likely to be calcualted as optimal by the dynamic programming algorithm.

As a separate matter, a comparison was made between the performance of two nonlinear programming algorithms that can be used to find the best air strike path in ISC's Operator Aided Optimization (OAO) aid. The background leading to this investigation is as follows: The nonlinear programming algorithm (Rosenbrock's method) previously used in ISC's OAO aid is a simple algorithm that does not require computation of derivatives. It is not as efficient (time and number of function evaluations to convergence) for most problems as the better derivative, i.e., gradient search, methods. Consequently, the following question arose: Suppose a sophisticated gradient search algorithm were used to find the best air strike path. How would performance using the gradient search algorithm in fully automatic mode compare with using Rosenbrock's method in fully automatic mode? ISC implemented a sophisticated gradient search algorithm was found to be less efficient than Rosenbrock's method. The most likely explanation is that gradient algorithms using approximation methods to find derivatives do not work well at the low precision required for competition with Rosenbrock's method on the air strike problem. The chain of reasoning leading to this conclusion is given in Subsection 3.4 of the report.

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1.0 INTRODUCTION

1.1 BACKGROUND

This is the fourth technical report by Integrated Sciences Corporation (ISC) as one of a group of contractors working on the Operational Decision Aids (ODA) program directed by the Office of Naval Research. The ODA program was initiated in 1974. It is intended to develop a variety of decision aids and test and evaluate their usefulness to the Navy. Although the program is not tied to any specific command and control hardware system, it has focused on the functions of a Task Force Commander (TFC) and his staff. The role of ISC has been to find ways to improve man-machine communication by allocating functions between man and machine that take advantage of their respective strengths.

ISC's early work on the ODA program explored the use of techniques by which a decision maker might express and communicate his perception of important relationships. ISC calls the particular techniques it has been developing "Sketch Models." A Sketch Model is essentially a "picture" that is first mentally visualized, and then drawn by a decision maker. As used here, the picture represents the decision maker's perception of the functional relationship between two or more variables, with the stipulation that the function be continuous in at least one dimension. Depending on the application, a Sketch Model can be, for instance, a single curve defining the relationship between two variables, or it can be a family of parameterized curves, or it can be a two-dimensional projection of the iso-"altitude" contours of a three dimensional function.

ISC's first study evaluated the ability of human operators to generate Sketch Models of bivariate Gaussian density functions from sampled data. In an experiment, a group of subjects were found capable of developing accurate Sketch Models of one type of well-behaved (i.e., unimodal and symmetric) three-dimensional function. These Sketch Models developed by the subjects from small samples of the underlying functions estimated those functions at least as well as, and in some cases better than, the statistical technique of maximum likelihood estimation.

A second study was undertaken to extend those results by investigating the ability of human operators to generate Sketch Models of less well-behaved functions, i.e., multimodal and unsymmetric. Experimental results gave a very strong indication that the subjects were able to produce accurate (as measured by percent volume error) Sketch Models for a highly irregular (multimodal and unsymmetric) function representing the joint detection capability of multiple sensors (Reference 1).

These first two studies had established that humans were adept at perceiving and sketching complex functional relationships when data that could be used to estimate the function were presented to the human in geometric/graphical format. The question became the following: How useful is this human capability? Therefore in the third study ISC proceeded to define (a) two decision aids that would use the human capability to solve an experimental problem that could also be solved by a fully automated algorithm, i.e., machine aided decision making and (b) an experiment that would compare decision performance with and without the aids (Reference 2). The two ISC-designed aids were called Operator Aided Optimization (OAO) using Nonlinear Programming (NP) and Operator Aided Optimization using Dynamic Programming (DP).

It is important to understand the nature and purpose of the experiments undertaken in the third ISC study for the ODA program. Although ISC used much of the structure and characteristics of a real-world situation, the experiment was deliberately limited and therefore, in a sense, artificial. The problem situation used in the experiment was the selection of (a) an air strike path through a field of ten enemy sensors and (b) aircraft speeds on each leg of the path. (Hereafter in this report, the selection of path and speeds is abbreviated to "selection of path.") Many aspects of real-world air strike planning were not included in the experimental problem, e.g., aircraft altitude, specific locations of enemy weapon systems and such real-world systems as electronic countermeasures. Also, the design of the experimental problems made certain perfect-information assumptions in order to simplify the analysis.

The experiment measured performance on solving 24 air strike problems for the following cases:

1. The operator solves the problem without aid from the computer.
2. Automated NP and DP algorithms solve the problem without aid from the operator.
3. The operator controls and guides one of the optimization algorithms in an iterative procedure for solving the problem.

Sixteen persons were used in the experiment. Twelve had technical educations, four did not. In some cases the straight-line paths devised by operators were so jagged that smoothing the paths would have been required before they could have been used for a real air strike. The research did not address this problem.

The principal findings of the experiment were:

1. The operators using the NP aid did significantly better than without the aid. The average improvement across all subjects and trials was 29% with a range of 9% to 123%. Performance was significantly different across operators but this was solely for unaided operation. Thus the aid served as an "equalizer." It enabled operators having relatively low scores without the aid to do as well as those who had relatively high scores without the aid.

2. Operators using the DP aid did significantly better than without the aid. The average improvement across all subjects and trials was 12% with a range of 3.5% to 27%.

3. The lack of a technical education was apparently not an impediment to good performance with or without either aid.

4. Operator aided optimization was significantly better than automated use of the NP algorithm for both types of rules used by the algorithm to select starting points.

5. The NP aid was less complex to use than the DP aid and operators generally preferred working with the NP aid to working with the DP aid. Operators using OAO with the NP aid found the global optimum on a higher percentage of trials than operators using OAO with the DP aid. The average time required to adequately train an operator to use either aid was about four hours.

ISC's conclusion based on these findings is that OAO is attractive to use when it is applicable because:

1. The operator can see what is happening during the optimization. With pictorial problem representation, he can make adjustments to the optimization procedure or results to compensate for limitations in problem representation more easily than he can when there is no pictorial representation.

2. The time required to train operators to use OAO with pictorial problem representation is relatively short and does not require technical knowledge of the algorithms.

Therefore, ISC believes that the logical next step is to identify those decision problems of Task Force Commanders for which OAO is applicable. This would include description of the problems and ways of representing them pictorially. The output of this process would serve as a basis for developing decision aid concepts that use OAO and interactive graphics. The new concepts could then be implemented and tested against existing methods for solving the same problems.

1.2 CURRENT WORK

The decision aids developed by ONR contractors under the ODA program make heavy use of interactive graphics. It was felt that knowledge about other military use of interactive graphics would enable us to evaluate and perhaps improve upon our own techniques as we are developing them. ISC therefore looked for other decision aids that make heavy use of interactive graphics and are being developed under sponsorship of agencies other than ONR. ISC inquiries found two such aids. The techniques used in these aids provide useful contrasts to the techniques ISC has developed. Summary descriptions of these aids plus an aid ISC is developing for the Army Reserach Institute are given in Section 2 of this report.

As a separate matter, a comparison was made between the performance of two nonlinear programming algorithms that can be used to find the best air strike path in ISC's OAO aid. The background leading to this investigation is as follows: The nonlinear programming algorithm (Rosenbrock's method) previously used in ISC's OAO aid is a simple algorithm that does not require

computation of derivatives. It is not as efficient (time and number of function evaluations to convergence) for most problems as the better derivative, i.e., gradient search, methods. Consequently, the following question arose: Suppose a sophisticated gradient search algorithm were used to find the best air strike path. How would performance using the gradient search algorithm in fully automatic mode compare with using Rosenbrock's method in fully automatic mode? ISC implemented a sohpisticated gradient search algorithm and compared the results of using it with the results of using Rosenbrock's method. Surprisingly, the gradient search algorithm was found to be less efficient than Rosenbrock's method. This work is reported in Section 3.

2.0 DEVELOPMENT OF INTERACTIVE DECISION AIDS SPONSORED BY AGENCIES OTHER THAN ONR

2.1 ISC GUIDELINES FOR PERFORMING THE TASK AND GENERAL RESULTS

ISC sought decision aid developments with the following characteristics:

1. The solution process performed by the system consisting of an operator, hardware, and software considers many interacting variables.
2. The operator's role is to structure the problem and/or guide the process through multiple steps to a solution satisfactory to him.
3. The system uses interactive graphics to represent the problem and to display potential solutions.
4. The problem is dynamic and the system helps the operator to consider problem dynamics.

Summary descriptions of three aids having these characteristics are given in subsections 2.2, 2.3, and 2.4.

A general observation resulting from our search is that there are few decision aids with the above-named characteristics being developed by or for agencies other than ONR. Most of the agencies and companies we checked that have the capabilities to develop such aids are instead developing systems that can be classified in one of the categories below:

1. Very large simulations which run on a computer without human interaction once the inputs are given to the simulation program.
2. Sophisticated data retrieval systems which are accessed by an operator at a display and which display retrieved or calculated data in pictorial format.

The Command, Control, Communications and Combat Effectiveness (FOURCE) model developed by the TRADOC Systems Analysis Activity (TRASANA) is an example

of the first category.[1] FOURCE is a division-level model of Army tactical combat with resolution to battalion level. It is two-sided and deterministic. The following are among the variables considered by FOURCE;

- Terrain
- Opposing orders of battle
- Operations and intelligence reports for both sides
- Movements of opposing forces
- Combat support by artillery, attack helicopters and close air support
- Target acquisition by sensors

FOURCE calculates and prints the results of engagements. The simulation consists of about 142,000 words of memory, over 200 subroutines, and more that 38,000 lines of code. Considering the entire development library, about 68,000 lines of code were developed to support the design, test, integration and initial use of the model.

TRASANA also has a line-of-sight model that fits the second category described above. The model stores a representation of terrain in matrix cell format and displays the terrain on a color raster display. Displayed terrain features include:

- Topographic contours
- Roads and rivers
- Levels of vegetation density
- Built-up areas

The model considers three types of sensors, namely, eye level, nap-of-the-earth (helicopters), and fixed wing aircraft. The operator uses a display peripheral to position a cursor on the displayed terrain and he also selects sensor type. The model then calculates and displays the matrix cells that can be seen from the given point with the operator-selected sensor. The visible region from a given point is usually not a single contiguous region because the model does take elevation into account. The system has additional capabilities including:

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[1]TRADOC stands for U.S. Army Training and Doctrine Command.

1. Calculation and display of regions visible from multiple designated points.

2. For a given set of points on a road, the model will calculate points on the surrounding terrain that can see either (a) 100% of the designated road points or (b) a designated percentage of the designated road points.

2.2 CALSPAN'S DEFENSE ANALYSIS SYSTEM (DAS)

2.2.1 Background

The Calspan Corporation of Buffalo, New York, has developed a system of computer and display hardware, software, and data bases to support and automate analysis of air defenses and their penetrability by airborne vehicles. This work was done under contract to Rome Air Development Center for the Intelligence Center Pacific and United States Armed Forces, Europe. The DAS concepts, hardware, and software enable a user to perform analyses which involve a broad variety of airborne vehicles including manned aircraft, remotely piloted vehicles and drones, and air-to-surface missiles. Specific objectives of the system are to:

1. Provide assessments of the threat potential of multiply-deployed enemy defenses against tactical air penetration.

2. Provide synthesis and evaluation of penetration routes and tactics.

3. Provide effective interactive control and display mechanisms to meet operational objectives, with near real-time capability when needed.

The operation of DAS was demonstrated to the authors during a visit to Calspan on 10 July 1978. Subsequent to our visit to Calspan, ISC received a functional description and data requirements for a proposed DAS system (References 3 and 4). Thus the DAS demonstrated to us and the proposed DAS differ in their levels of capability; the proposed DAS would be the more capable system. The DAS description presented here applies to the observed system and not the proposed DAS.

2.2.2 DAS Functions

There are four DAS functions that perform analytical processing of various types on input data and control parameters and generate intermediate results or user outputs. These are:

- Scenario definition
- Threat evaluation
- Corridor/route/tactics development
- Penetration evaluation

The scenario definition function pictorially displays defense system components on a map of the relevant geographic area. For each penetration type/altitude of interest, the display shows the maximum effective range circles of all defense elements capable of engaging the specified penetrator.

The threat assessment function calculates attrition related costs for each transition by a penetrator vehicle between grid points of the defended area. The following factors are considered by the algorithm:

- Penetrator type, speed and altitude
- Whether ECM equipment aboard the penetrator vehicle is on or off.
- Capabilities of each defense element against the penetrator vehicle

The threat assessment data constitute input to route/tactics synthesis and penetration evaluation. The route/tactics synthesis function calculates the optimal route, tactics, and cost for a designated penetrator vehicle type proceeding between designated origination and target points. The route is shown on the geographic display. Tactics specified for each route segment between grid points include altitude, speed, and whether ECM equipment is on or off. The route/tactics synthesis function also calculates and displays corridors which contain route and tactics solutions within a specified level, e.g., 5% or 10%, of optimum cost.

The penetration evaluation function enables the user to interactively perform detailed sensitivity analysis. When DAS is in this mode, it generates

and displays sets of route/tactics/cost combinations based on operator inputs to constrain or influence the optimal solution developed by the route/tactics synthesis function.

2.2.3 Data Inputs and Outputs

The following data are resident within the DAS system on a long-term basis:

Penetrator Vehicles

- Speed, altitude, fuel capacity, and rates of fuel consumption versus flight regime parameters
- Performance characteristics of ECM aids carried
- Signatures detectable by defense detection systems

Air Defense Systems (Surface to Air Missiles and Guns)

- Detection and track performance
- Response times
- Weapons ranges
- Missiles/projectile accuracy and lethality
- Susceptibility to countermeasures

Cost Function Data

An engagement model calculates cost to the penetrator for each combination of penetrator and air defense system characteristics. The cost data are expressed in terms of expected number of lethal hits per unit of distance traveled and are stored as a function of up/down range distance and lateral offset from each defense site. The probability of penetrator survival for a complete route is calculated from the summation of the expected number of lethal hits.

Geographic Data

Geographic data input include air bases, coastlines, political boundaries, and locations of defense systems.

Operator inputs made while using the system include the following:

- Origin and target destination of penetrator vehicles
- Penetrator type
- Smoothed routes having fewer changes in flight profile and tactics than the optimal route
- Manually-input routes and tactics.

Output data include the following:

- Map with locations of defense systems and maximum range circles centered on each defense system for the penetrators specified by the operator.
- Optimal route and tactics from selected origin to target and return. The optimal route is displayed as connected grid points. Tactics are given for each route segment between grid points in terms of speed, altitude, and whether penetrator ECM equipment is on or off.
- Corridors of near-optimal route points (points on routes within an analyst-specified tolerance of optimal cost)
- Estimated attrition for route/tactics combinations

2.2.4 Operator's Work Station

The work station where the operator manipulates the DAS system contains the following components:

- A high resolution vector/character display with a light pen which enables the operator to select or indicate a point on screen.
- A digitizer tablet which enables the operator to rapidly transmit map data points on the display to the central data processor.
- A function keyboard to select standard processing sequences.
- An alphanumeric CRT display with associated keyboard for data entry/display capability, and display of instructions, menus, and critical messages to the operator.

2.2.5 Analysis Process

The analysis process begins with operator selection of a geographic area and the defense order of battle stored in the computer for that geographic area. The operator also selects tactics options consisting of penetrator type, ECM equipment carried aboard penetrator vehicles, and speed and altitude constraints. He can then request any of the following displays:

1. Threat coverages corresponding to the selected tactics options. The display will show as a function of penetrator altitude maximum-range circles around all the defense systems located on the display or any operator-specified subset of defense systems such as surface-to-air missile sites of a given type.
2. Cost density, that is, areas where cost density exceeds an operator-selected threshold level.
3. Selected elements of the battle area such as restricted zones where penetrator vehicles may not go and the forward edge of the battle area.

The operator can then use the light pen to select the origin and destination (target) points for the penetrator vehicles. Upon request, the computer will calculate and display on the graphics terminal the optimal route and defense maximum-range circles that intersect the optimal route (a dynamic programming algorithm is used to do the optimization). Tactics for each leg of the route, cost for the route, flight distance and time, and fuel expended are shown on the alphanumeric display.

Next, the operator can request a "corridor" display of points on routes that are less than optimal by an operator-specified percentage. The operator uses the corridor display as a reference for evaluating alternatives to the optimal route. The alternatives include:

1. A computer smoothed version of the optimal route. Smoothing is done to make the speed, altitude, and course changes from leg to leg more feasible than the sharp changes that are likely to be calculated as optimal by the dynamic programming algorithm.
2. A manually selected route defined with the light pen and based on the corridor display. The computer then calculates for each operator-specified leg the optimum tactics consisting of speed, altitude and whether ECM is on or off, plus the cost for comparison with the computer-defined optimum.

An aid during the operator's analysis is an alphanumeric display of cumulative cost at any specified point on a designated route. This enables the operator to determine and avoid high cost regions.

Tables 1 and 2 are taken from Appendix B of Reference 3. Although Reference 3 is a functional description of the DAS proposed by Calspan for Air Force use, Tables 1 and 2 do correspond very closely to the DAS capabilities demonstrated during the authors' visit to Calspan.

2.2.6 Limitations

Important limitations of the existing Calspan DAS are listed below. The system proposed in Reference 3 would have capabilities to handle or remove these limitations.

1. The existing cost functions cover only a few penetrator vehicle types and defense system types among the many systems in the inventories of friendly and potentially hostile forces. For example, a simplified generic model of defense fighter aircraft effects is included in the defense systems modeled. Development of all the needed data sets requires extensive simulation models and highly detailed sensor, weapon, and penetrator vehicle data.
2. There are no defense command and control models. For example, in the existing model a single penetrator is engaged by all defense systems when the penetrator is in an area of overlapping defense coverage. Also, the cost calculated for a flight of n simultaneous penetrators is simply n times the cost for a single penetrator. Thus the model does not account for the degradation of defense capability when multiple simultaneous penetrators confront the defense.
3. The model does not treat communications netting of defense elements to account for the alerting of inner defenses by outer defenses that detect an approaching flight of penetrators.
4. The model cannot treat defense elements whose existence is known but whose locations are only known within an uncertainty region.
5. The DAS enables the operator to find a minimum cost way of using a given offensive force to penetrate a defense around a single assigned target. However, DAS is not explicitly configured to aid the operator in finding the best subset of offensive assets from a larger set to penetrate a defense.

Table 1. Typical Threat Evaluation Sequences

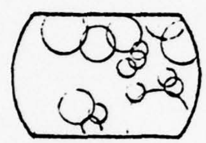
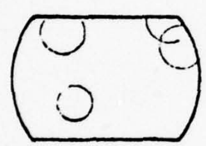
OPERATOR ACTION	GRAPHICS DISPLAY	A/N DISPLAY	OPERATOR CAN INFER
A. SELECT: Enemy OB data set and geographic area		Available options Operator's choices	
B. SELECT: Tactics options		Available options Operator's choices	
C. REQUEST: Display of threat coverages (circles, with radii for worst case for selected tactics options)		As commanded by keyboard or light pen... identification of and data about threats	General geographic distribution of threats
D. SELECT & REQUEST DISPLAY: Subsets of data in the step C display (select by threat type, specific ID's, geographic area)		Options available to operator. Record of choices	As above, but selectively.

Table 1. Typical Threat Evaluation Sequences (Cont.)

OPERATOR ACTION	GRAPHICS DISPLAY	A/N DISPLAY	OPERATOR CAN INFER
E. REQUEST Threshold displays of cost density... illuminated areas where cost density exceeds operator-selected threshold level ITERATION over varying threshold levels	 High threshold  Med threshold  Low threshold	Values of thresholds	Geometry patterns of risk-related costs (in contrast to displays C, D... which do not reveal variations of costs with different circles) In particular: regions of very high and very low risk These displays may be varied with tactics options, by return to step B for change.

Table 2. Typical Tactics Development/Evaluation Sequences.

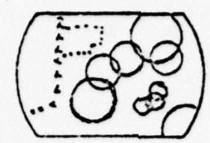
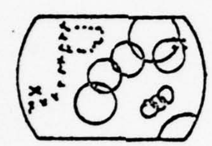
OPERATOR ACTION	GRAPHICS DISPLAY	A/N DISPLAY	OPERATOR CAN INFER
A. REQUEST: Displays of selected elements of battle area: enemy threat zones priority targets FEBA restricted zones etc.	 Selected display	Record of operator choices	General threat scenario
B. SELECT: (With light pen or equivalent, or by keyboard entry) IP target location tactics choices selected threat data (actual OB, or hypothetical data from data set generated outside this step)	 As above, plus IP and target points	Image of operator input instructions or data	As above, but with IP and target locations displayed in context
C. REQUEST: Optimal Route plus: selections among standard overlays; special overlays (tactics coded onto route; critical segment of route; etc.	 Optimal route plus any selected overlays	Cost for optimal route. Identification of threats that intersect optimal route. Flight distance and time. Fuel expended, etc.	General character of a good flight route, set into context. General choices of tactics along route, critical segments. Nominal value of "cost"

Table 2. Typical Tactics Development/Evaluation Sequences (Cont.)

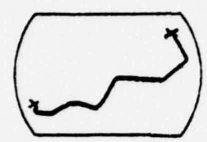
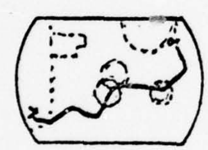
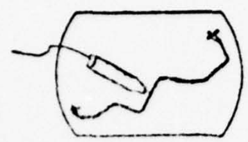
OPERATOR ACTION	GRAPHICS DISPLAY	A/N DISPLAY	OPERATOR CAN INFER
D. REQUEST: Corridor display (Points on routes that are essentially equivalent to optimal)	 Near-optimal points overlaid on optimal route		Width sensitivity of optimal route. Secondary as well as primary corridors of good approaches. Potential for smoothing of optimal route.
E. SELECT: Reference route REQUEST: Evaluation Operator Choices o Original optimal route o Computer-smoothed version of optimal o Manually selected route (e.g., defined with light pen) based on the corridor display.	 Reference route	Cost for reference route Identification of threats that intersect reference route. Flight time, distance Fuel expended, etc.	Cost of reference (smoothed) route vs optimal.
F. REQUEST: Selected overlays on reference route, e.g.: relevant-threat zones tactics codes FEBA etc.	 Reference route with selected overlays	As above, plus identification of relevant threats	Effective threat environment for the chosen reference route

Table 2. Typical Tactics Development/Evaluation Sequences (Cont.)

OPERATOR ACTION	GRAPHICS DISPLAY	A/N DISPLAY	OPERATOR CAN INFER
G. EVALUATE: Cumulative cost along reference route, and implications with respect to the threat environment	 Selection of points	Costs at selected points	Threat profile along reference route. Critical regions... segments of rapid changes in cost. Qualitative association of cost/risk with specific weapons.

H. ITERATION OF THESE STEPS TO EVALUATE REAL OR HYPOTHETICAL CHANGES:

EVALUATION OF EFFECT OF AN ARBITRARY CHANGE IN REFERENCE ROUTE:

Return to step D or E, then proceed

EVALUATION OF SUCH CHANGES AS:

REMOVAL OF SPECIFIED THREAT OR THREATS (CHANGE IN ASSUMED ENEMY OB);
CHANGES IN TACTICS OPTIONS
ETC.

(a) Return to Step A, B or C and proceed, to get new optimization and complete the full study sequence

(b) Return to Step D or E for studying effects without a change in the reference route.

2.2.7 Status

Calspan developed the functional descriptions, systems specifications, and plan for implementing an advanced capability DAS at several Air Force sites. This work was completed in May 1978. The Calspan effort was then terminated short of delivery of any operating software of implementation of any capabilities due to funding difficulties experienced by the sponsor.

In January 1979 Rome Air Development Center issued a request for proposal to industry to accomplish the following:

1. Examine the methodology and concepts related to the function of defense/penetration analysis as it is currently done in the tactical air forces.
2. Define the functional processes from which algorithmic procedures suitable for translation into computer programs can be developed.
3. Recommend the assistance or changes needed to make the defense penetration analysis function more timely, accurate, and complete.

Thus, the work accomplished by Calspan will serve as a stepping-stone for the new effort in penetration analysis.

2.2.8 Commentary

There are significant differences between Calspan's DAS and ISC's OAO aids that prevent making straightforward comparisons. Some of these are listed below:

1. The Calspan and ISC developments were done for different reasons. The purpose of the Calspan work was to develop requirements and specifications for DAS that would lead to procurements by the U.S. Air Force. The purpose of ISC's work has been to develop decision aiding concepts using OAO and to compare the OAO mode of decision making with unaided and fully automated modes.
2. Calspan has not conducted formal performance testing of DAS using human subjects to operate its system. ISC has conducted an experiment with human subjects to compare OAO performance with unaided and fully automated performance.

3. DAS treats more factors than ISC's OAO aids. The ISC aids solve for the geographic route and aircraft speeds considering the detection capability of enemy sensors. DAS solves for route, aircraft speed, aircraft altitude, and whether on-board electronic countermeasures equipment should be on or off. DAS considers detection and track capability of enemy sensors, weapons capability of enemy missiles, guns, and fighter defenses, and defense susceptibility to electronic countermeasures.

DAS incorporates two techniques that are worth considering for inclusion in future aids that might be designed for the ODA program. One is a modified version of the standard dynamic programming algorithm that speeds the solution process. The other technique is the calculation and display of the corridor containing suboptimal path solutions around the computer calculated optimal path as described in Subsection 2.2.5.

2.3 LAWRENCE LIVERMORE LABORATORY'S TWO-SIDED TACTICAL ANALYSIS GAME "MINIJ"

2.3.1 Background

Lawrence Livermore Laboratory is developing two tactical analysis models in order to explore the military utility of different tactical nuclear weapons and the doctrine and tactics appropriate for combined conventional and nuclear combat. The two models are called JEREMIAH and MINIJ. Specific problems areas to be addressed by using these models include:

1. Cooperative tactics for conventional/nuclear mixes in (a) first use, (b) second use.
2. Target acquisition and "real time" tactical nuclear weapon (TNW) resource allocation.
3. Conventional/nuclear weapons mix options.
4. Survivability of TNW's
5. Exploitation of TNW use to regain initiative on the battlefield.

Some characteristics which differentiate the models are given in Table 3 below. The remainder of this subsection treats MINIJ because it is more interactive and display oriented at present than JEREMIAH.

Table 3. Characteristics Which Differentiate JEREMIAH and MINIJ

Characteristic	JEREMIAH	MINIJ
Terrain modeled	Elevation, cover, concealment, mud, fog, roads, cities	Elevation, cover, cities
Scenario area/ resolution	500 Km^2/100 meters	400 Km^2/2000 meters 40,000 Km^2/20,000 meters
Display	Television shows dynamic replay of movements and actions simulated by computer	Computer-driven raster display shows dynamic replay of movements and actions simulated by computer
Interactive Control	Teletype input to the computer	Digitizer tablet for specifying points and units on display; function keyboard for specifying types of user input
User	One analyst with full information	Two opposing players each operating with partial information about his opponent
Computer type	Large scale computer (CDC 7600)	Minicomputer (Varian 73)

2.3.2 Player's Work Station

There are four hardware elements used by a MINIJ player, namely a teletype keyboard, color raster display, digitizer tablet, and function keyboard. The teletype keyboard is used to:

1. Schedule MINIJ on the computer.
2. Select a preprogrammed scenario. The scenario includes deployment of units on the terrain.
3. Make changes to the default data set. This includes adding and subtracting units on the terrain and changing unit military characteristics such as speed and "hardness" (resistance to damage).

The display shows the terrain, unit deployments, dynamic movement of forces, detections of opposing units, and "kills" resulting from battle. The player uses the function box to specify the mode of digitizer tablet use, e.g., planning, and he uses the digitizer tablet to specify units and locations on the display. Once the scenario has been started, all inputs are made by the function box and digitizer tablet.

2.3.3 Terrain and Forces Simulated

Three terrain features are simulated, namely, elevation, cover, and cities. Elevation is shown by topographical contours on the display. Cover is stored in the computer for each resolution cell as a percentage of complete cover. The density of green X's on the display corresponds to the density of cover in an area. Cities are represented by three concentric blue circles. All cities are uniform in size.

Eight types of combat forces are simulated. These are:

- Tanks
- Nuclear artillery, type I
- Nuclear artillery, type II
- Anti-tank missile units
- Helicopters
- Ground launched cruise missiles

- Manned tactical aircraft with nuclear bombs
- Nuclear ballistic missiles

The helicopters fly at 20 meters above the terrain. The simulation can handle up to 20 units per side. Each unit contains integer elements of force types. For example, a single unit might consist of five tanks. Force locations and movements are specified at the unit level.

2.3.4 Player Actions and Engagement Simulation

Player actions begin after (a) the preprogrammed scenario has been scheduled and (b) any changes to the default data on force structures and unit characteristics have been made. Each player sees the terrain and his own forces. He then defines unit movements and nuclear artillery fire to defend a position or to take control of a position not currently held.

The player uses the digitizer tablet to designate a unit he wishes to move. The position of the digitizer corresponds to the position of a circular cursor on the display. The player moves the cursor to the position of the unit he wishes to move. He then uses the cursor and keys on the function keyboard to define a movement path to an objective. The player can also designate up to five groups of units. The simulation will cause all units to move along a user-specified path at the user-designated speed.

Manual and automated modes of nuclear artillery fire are available. In manual mode the player moves a weapons effect circle from the location of a nuclear artillery unit to a target. He may then select one of five nuclear yield levels for the weapon. The display shows a maximum range arc, "city-safe" radius, and "city-kill" radius. If the player selects automated mode, an algorithm in the computer will assign nuclear fires to recently detected targets on the basis of a "value map" of targets and avoidance of own units and cities. The automated mode becomes operative after the engagement simulation begins.

MINIJ is an event-driven simulation. An exception is that a reconnaissance scan for enemy units is performed at times not exceeding 0.03 minute of

problem time. The engagement simulation begins after both players have completed their planning. Decisions to fire or not fire at detected units are made automatically, that is, without user input. Also, decisions to fire do not affect previously planned movements. Engagement results are determined by a random number draw from the applicable probability distribution and, consequently, results are stochastic and not deterministic.

During the automated play of the game a player sees the following:

1. Movements of own units
2. Detection locations and tracks of enemy units while contact is held. A star symbol shows the last known location of an enemy unit when contact is lost.
3. Conventional fire is indicated by small orange circles. Conventional kills against own units are indicated by white "C's."
4. A nuclear weapon laydown resulting from automated mode of nuclear weapon use is shown as a circle. Large "N" symbols represent units/cities killed by nuclear effects.

After the simulation has begun, a player may stop the simulation to change previously made movement plans or to execute a manual laydown of a nuclear weapon on the location of a detected target or a location where a target is suspected to be. While the simulation is stopped, a player may also get a detailed tabular printout of unit status information from the teletype. Engagement simulation resumes when the player completes his planning changes. Scenarios with actions of both players and engagement results can be stored on disk and replayed when called.

2.4 ISC's TACTICAL ON-LINE MANEUVER MODEL (TOMM)

2.4.1 Background

ISC is developing a Tactical On-Line Maneuver Model (TOMM) for the Army Research Institute. TOMM is a division-level model that is highly interactive and is oriented toward graphical analysis of Army battlefield situations.

The purpose of TOMM is to enable a tactical planner to create hypothetical tactical situations via interactive computer graphics and to evaluate

the results of events. The computer and display combination provides input guidelines, shows dynamic replays of actions, and displays outcomes of events. Thus, TOMM is aimed at exploiting the user's tactical knowledge and the computer's calculation/display capabilities.

The purpose of the research is to provide suggestions for using displays to assess alternative deployments of complex friendly forces against expected or possible enemy movements. If the user of computer graphics plots a tactical situation (including terrain and unit movements), then computer calculations can help by indicating likely effects of terrain on unit mobility and on combat effectiveness. In addition, computer algorithms can help the user to see emerging patterns by displaying dynamic replays of events and probable outcomes of engagements. The goal is to obtain quick and reasonable answers to "what if?" battlefield questions.

2.4.2 User's Work Station

There are three hardware elements used by a TOMM tactical planner, namely:

- Four color, vector graphics display
- Trackball
- Function keyboard

The planner uses the trackball and keyboard to create terrain, opposing orders of battle, and movements of forces. These are all shown on the display as they are being created. The computer simulation causes the display to dynamically show the replay of movements and tactical events consisting of detections and engagements. Keyboard and trackball are also used to call up specialized graphical displays that help the planner to assess a tactical situation.

2.4.3 Terrain and Forces Simulated

The system enables the planner to use the trackball and the function keyboard to define the following terrain types within a 20 Km by 20 Km scenario area:

- Clear
- Forest

- Inner Hill/Outer Hill Regions
- City
- Lake
- River
- Road

Rivers appear as lines and roads as parallel lines; all the other terrain types are represented as closed contours. Hills are differentiable into inner hill contours and outer hill contours. The military crest is considered to exist at the inner hill contour. The system recognizes hybrid terrains composed of (a) forest and inner hill contours and (b) forest and outer hill contours. The differentiation of hills into inner and outer contours impacts on the detection model and the model of area of battlefield effectiveness for each unit. The planner also uses the trackball and function keyboard to define and deploy brigades, battalions, and companies of armor and infantry and battalions and batteries of artillery.

2.4.4 User Actions and Engagement Simulation

The planner first creates the terrain and orders of battle.[1] He then creates movement plans for each unit on one side by using the trackball to define a path and the function keyboard to specify the unit's times of arrival and departure at each node on the path. The planner also designates an offensive or defensive mission for each unit. He can specify a group of units and cause the group to move in accordance with one of four group movement rules. When the planner has finished defining the movements of individual units or groups of units, he can call for a dynamic replay showing the simultaneous movements of all units. He can interrupt the replay at any time to change a unit's movements so that the joint movements conform to his concept of a coordinated tactic.

[1] In actual battlefield use of a TOMM system these tasks might be performed by specialists. In that case the terrain and orders of battle would be stored in the computer for later use by intelligence and operations personnel who define and analyze tactical alternatives.

When the planner has finished defining movements for one side, he repeats this process for the opposing side. However, this time the simulation stops each time a detection is made by one side or the other according to an algorithm which considers terrain and unit characteristics. The display shows the detecting and detected units. The planner then has an opportunity to change movements previously planned for any unit on either side.

When the planner has finished defining movements for both sides, he then initiates a replay that shows movements by both sides. This time when detections occur, the planner decides whether engagement occurs. If he elects to have an engagement occur, he also specifies the units taking part in the engagement. Computer algorithms calculate the proportion of each unit's fire power that is used against opposing units and the attrition of fire power and supplies that results from engagement for each unit. At the end of a simulated combat period, the planner has the opportunity to redefine movement and combat posture for any unit.

Ultimately the planner completes all changes and is satisfied that the movements and engagements represent what would be likely to happen if both sides pursued the coordinated tactics he specified. This entire process constitutes creation and analysis of one hypothetical tactical situation. The planner may then wish to construct and analyze other hypothetical situations.

2.4.5 Special Data Displays

The planner can elect to call up data displays during the planning process. The displays help him to make action decisions. Below are brief descriptions of the main data displays available.

2.4.5.1 Terrain Mobility. Terrains are classified as GO, SLOW-GO, VERY SLOW GO, and NO-GO according to a set of rules. Mobility for each unit type in each closed contour terrain type (i.e., all terrains except roads and rivers) is displayable upon user command. The codes are:

Terrain	Code
GO	None
SLOW-GO	Dotted lines, crosshatched
VERY SLOW-GO	Dot-dash lines, crosshatched
NO-GO	Solid lines, crosshatched

2.4.5.2 Unit Range Contours. The planner can call for contours representing the potential future locations of one or more designated units. The contours take into account terrain mobility for the designated unit types and sizes.

2.4.5.3 Unit State. The planner can call for displays of unit state. These include alphanumeric display of the following:

- Symbol for the unit type and size
- Label
- User designated mission
- Percentages of full strength firepower and endurance remaining

He can also call for graphical display of percentages of full strength firepower and endurance remaining at four equally spaced times in the most recent 30 minutes.

2.4.5.4 Detection Regions. There are rules defining when one unit can detect another. The planner can designate an x,y location and call for display of the region within which other units will be detected from the designated location.

2.4.5.5 Area of Battlefield Effectiveness. There are rules defining the region that a designated unit type in a designated terrain type can effectively take under fire. The planner can call for a display of this region.

3.0 COMPARISON OF GRADIENT AND NON-GRADIENT ALGORITHMS FOR AUTOMATED NONLINEAR PROGRAMS

3.1 BACKGROUND

The nonlinear programming algorithm (Rosenbrock's method) in ISC's OAO aid (Reference 2) is a simple algorithm that does not require computation of derivatives. It is not as efficient (time and number of function evaluations to convergence) for most problems as the better derivative methods, i.e., gradient search methods. The utility function used in the air strike problems is smooth and continuous. Therefore, a gradient search algorithm could be used to optimize the best air strike path according to this utility function. This utility function, which incorporates a tradeoff between minimizing the probability of detection by enemy sensors and maximizing the fuel remaining upon arrival at the target, is given by:

$$U(F,P) = \begin{cases} \left[\dfrac{(a-b)D - F}{2(a-2b)D}\right]^{(.01+4.95P)}, & \text{if } (a-b)D - F \geq 0 \\ (a-2b)D - F, & \textit{otherwise} \end{cases} \qquad (1)$$

where

- F = total amount of fuel consumed upon arrival at target
- P = cumulative probability of detection by enemy sensors
- D = distance between strike launch point and target
- a = fuel allowance/n.m. (29.7 lbs/n.m.)
- b = fuel consumption/n.m. at an achievable speed resulting in the lowest fuel consumption per unit distance traveled (8.3 lbs/n.m. corresponding to a velocity of 250 knots).

Consequently, the following question arose: Suppose a sophisticated gradient search algorithm were used to find the best air strike path. How would performance using the gradient search algorithm in fully automatic mode compare with using Rosenbrock's method in fully automatic mode? ISC implemented a sophisticated gradient search algorithm and compared the results of using it with the results of using Rosenbrock's method. This work is reported in this section.

3.2 TEST PROCEDURE

A new automated gradient algorithm called MINI was selected for use on the air strike path optimization problem. (See the Appendix for a description of MINI.) MINI was tested in the same way as the previous non-gradient algorithm, here called ROMIN (for Rosenbrock minimization, the optimization procedure used). Performance on five trials of 15 minutes for each of twelve problems was obtained using the Parabolic Starting Point rule described in Reference 2. The problems used were the same as those used previously. The three parameters EPS (convergence criterion), DFAC (relative step size), and ACC (relative accuracy) discussed in the Appendix were varied in an attempt to maximize the performance of MINI on the problems. Initially DFAC was fixed at 0.0005, a value found to work well in ISC's other uses of gradient approximation; later DFAC was increased to 0.005 for reasons discussed in the next subsection. The integration accuracy parameter ACC was set to 0.001 for three-digit accuracy or to 0.0001 for four-digit accuracy. In combination several values of the convergence criterion EPS were tried as seen in the next section.

Performance on the 15-minute trials was measured in two ways:

1. The utility $U(t)$ of the best-solution-to-date at the end of each minute t.
2. The time-average of best-utility-to-date according to the "scoring rule" formula:

$$\overline{U}(t) = \frac{1}{T}\sum_{t=1}^{T} U(t) \tag{2}$$

Performance figures for each problem were obtained by averaging over the five trials on that problem. In order to obtain overall performance figures across problems, these average results for each problem were first normalized by the same factors as in the previous report (i.e., best operator-aided performance on the problem) and then the normalized figures were averaged across the twelve problems. These normalized results on the best-utility-to-date and the time-averaged scoring rule criteria were used both to compare the performance of MINI with different choices of parameters, and to compare MINI with the previous algorithm ROMIN.

3.3 RESULTS AND ANALYSIS

The first phase of this study involved varying three parameters EPS, ACC, and DFAC in an attempt to maximize the performance of the new algorithm MINI, as discussed in the previous subsection. As mentioned there, the gradient approximation parameter DFAC was initially fixed at 0.0005 while the other two parameters were varied. Normalized values for best-utility-to-date and time-averaged scoring rule (Equation 2) at the end of the 15-minute trial periods are shown in Table 4, averaged over all problems.

Table 4. Performance of MINI With Various Choices of Parameters (DFAC=0.0005).

	ACC=0.0001		ACC=0.001	
EPS	Best-to-Date	Scoring Rule	Best-to-Date	Scoring Rule
0.01	—	—	69.9	60.7
0.05	65.9	54.4	71.4	62.3
0.1	68.2	56.4	71.2	63.7
0.2	63.6	54.2	—	—
0.5	54.4	48.7	—	—

Dashed lines indicate no trials were made with those combinations of EPS and ACC. Trials were limited by the 15 hours of computer time required to test each combination (5 trials on 12 problems for 15 minutes each). Examining these results, the decision was made to use ACC=0.001 and EPS=0.1 as the parameter values for MINI. No larger values of ACC were tried since these would give less than three-digit accuracy in the results, which was felt to be necessary both for true optimization and for accurate comparison to the previous results from ROMIN. As a result of the low accuracy value chosen (ACC=0.001), it was decided to increase the parameter DFAC to 0.005 in the gradient approximation. This improved the performance figure for best-utility-to-date from 71.2 to 72.2, while decreasing the scoring rule result from 63.7 to 62.8. The decision was made to use ACC=0.001, EPS=0.1, and DFAC=0.005 as the final parameters.

For direct comparison with the results on the non-gradient algorithm ROMIN reported in Reference 2, it was then necessary to undo an improvement that had been made in the system's random number generator since the date of the last report. This degraded the performance of MINI slightly; the performance figures given above as 72.2 and 62.8 became 71.7 and 61.4, respectively, for the chosen set of parameters.

Figure 1 shows a plot of normalized best-to-date utility versus time for ROMIN and MINI (with the chosen parameter values). The curves are significantly different at the 1% level by the Wilcoxon matched-pairs, signed-ranks test. The plot verifies that the non-gradient routine ROMIN is, surprisingly, superior to MINI at all times. Superiority of ROMIN is 1% at minute 1, 36% at minute 2, and then levels off at about 11 or 12% after minute 7. Comparing normalized best-to-date utility for each of the 12 problems separately, at the end of the 15-minute trial period ROMIN had a higher score on all but one problem. This 15th minute score superiority on the problems is significant at the 5% level on the Wilcoxon test. (It should be mentioned that the performance of ROMIN shown here differs very slightly from that shown in Reference 2 due to improvement in the clock routine incorporated in both ROMIN and MINI.)

Figure 2 shows a plot of normalized time-averaged utility calculated according to the scoring rule, versus time, for ROMIN and MINI. Again, the curves are significantly different at the 1% level on the Wilcoxon test, with ROMIN again showing superiority at all times. The superiority is 1% at minute 1, 22% at minute 2, and slowly falls to 15% at minute 15. A comparison of minute-15 results again shows that ROMIN outscored MINI on all but one problem.

3.4 CONCLUSIONS

It is clear from the results of the previous subsection that the non-gradient algorithm ROMIN is to be preferred to the gradient algorithm MINI. Since the performance of MINI was poorer than expected, reasons for this failure were sought. One possible explanation is that MINI has four parameters which affect convergence while ROMIN has only one. Testing three values for each parameter of MINI (as was done with ROMIN) would require $3^4 = 81$ combinations

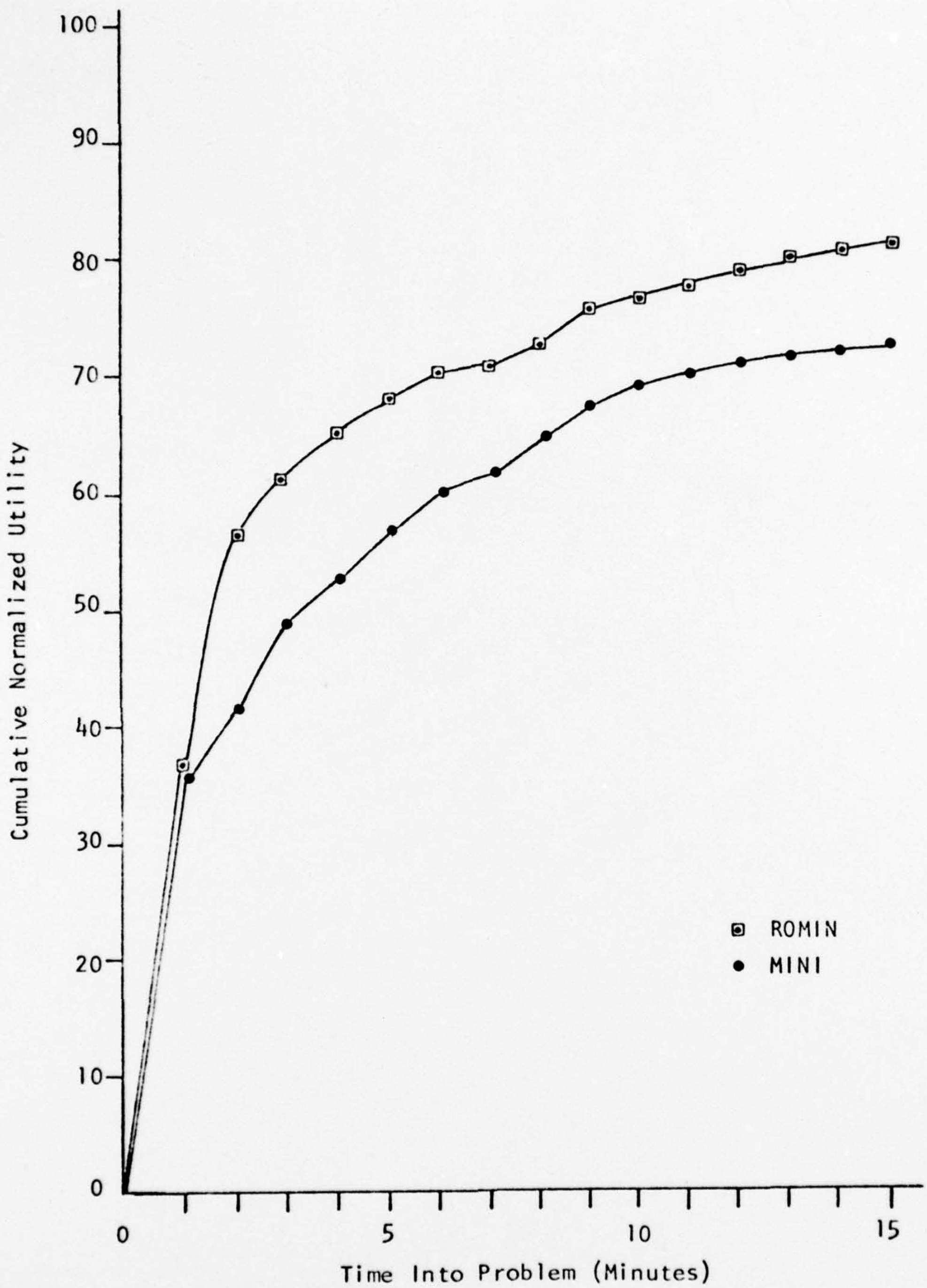


Figure 1. Best-to-Date Normalized Utility Versus Time.

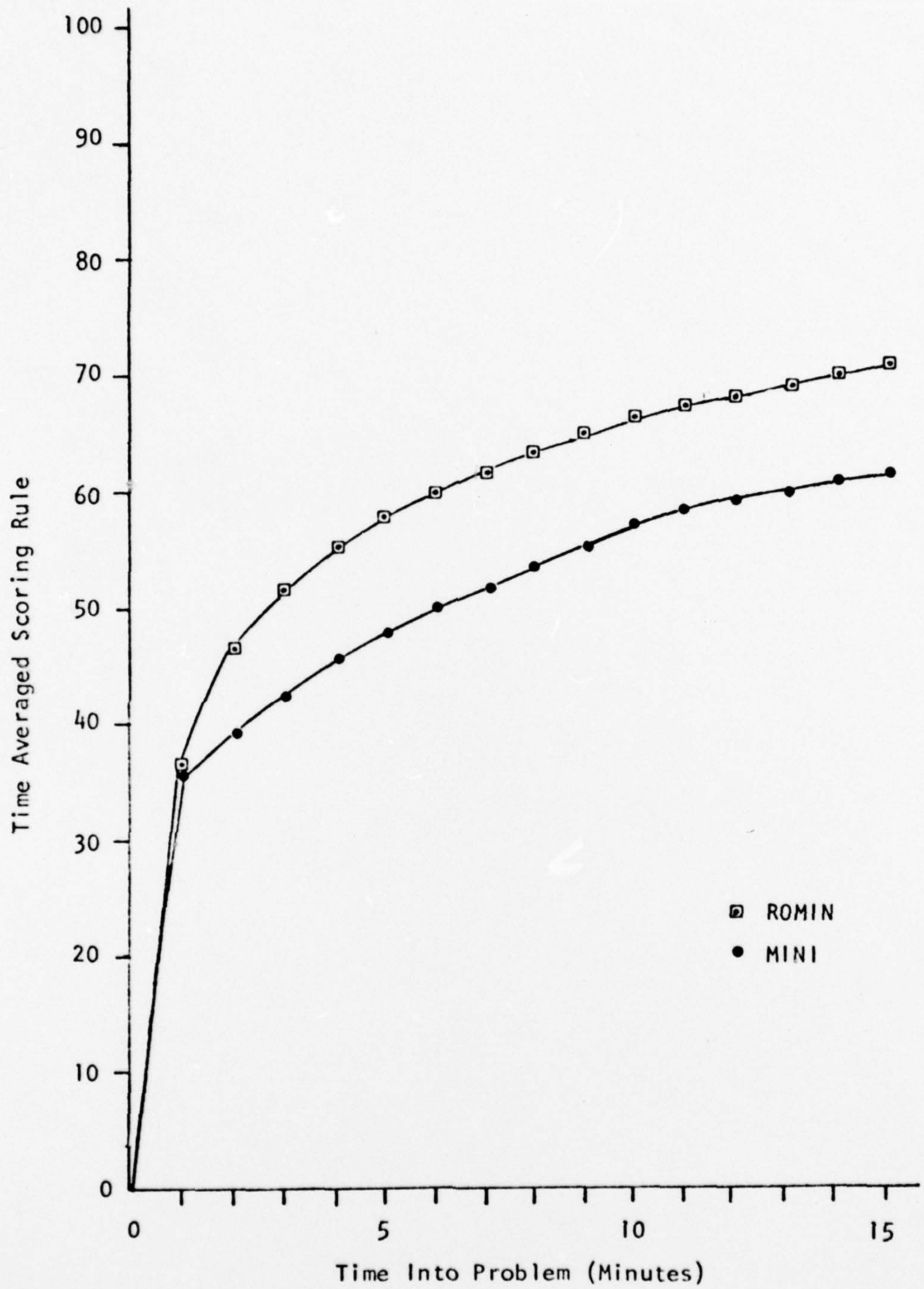


Figure 2. Time Averaged Scoring Rule Utility Versus Time.

to be run, with 15 hours of computer time per combination, which is obviously impractical. Thus, the combinations of parameters chosen for testing are probably not optimum. Nevertheless it is clear, from the pattern of results obtained from those parameter values that were tried, that even an optimum choice would probably not cause MINI to outperform ROMIN. Thus, some other explanation seems necessary.

The most likely explanation is that gradient algorithms using approximation methods to find derivatives do not work well at the low precision required for competition with ROMIN. The chain of reasoning that leads to this conclusion is as follows:

1. For MINI to compete successfully with ROMIN under the constraint of 15 minutes per problem, MINI must perform function evaluations approximately as fast as ROMIN.
2. For MINI to perform function evaluations as fast as ROMIN, MINI must calculate the optimized utility function to only three-or four-digit accuracy as was done with ROMIN. (If MINI calculated the optimized utility function to five-or six-digit accuracy, it would be much slower than ROMIN and therefore MINI'S performance would be much worse than ROMIN'S under the time constraint of 15 minutes per problem).
3. The finite-difference derivative approximations used in MINI require a small relative step size (the parameter DFAC previously discussed) in order to correctly estimate the derivatives. A larger relative step size in the derivative approximation leads to a breakdown in the assumption that the utility function can be approximated by a straight line spanning the step. This assumption is necessary for simple and accurate derivative approximation.
4. A small relative step size in the derivative approximation may be meaningless in a utility function which is only evaluated to three-digit accuracy. This leads to very poor estimates of derivatives.

MINI would probably perform better than ROMIN in either of the following situations:

1. MINI will find a better "best path" if time constraints are removed.
2. MINI will converge more quickly if high precision function evaluation is used by both ROMIN and MINI.

Thus, we are led to the conclusion that derivative approximation and low-precision function evaluation are incompatible, a topic seemingly ignored by the literature, and so non-gradient algorithms like ROMIN are superior in this case. Also, it is reasonable to infer that:

SINCE neither the automated general purpose gradient nor general purpose non-gradient algorithms tested were able to outperform an operator controlling and guiding an optimization algorithm

THEN only an automated optimization algorithm highly tailored to the air strike problem could outperform an operator who guides and controls a general purpose algorithm. A significant effort would be required to develop such a highly tailored algorithm.

APPENDIX

APPENDIX

DESCRIPTION OF THE GRADIENT ALGORITHM "MINI"

Prior to selection of the specific gradient algorithm, consideration was made of the difficulty of computation of the necessary derivatives of the utility function with respect to the 13 independent variables, i.e., with respect to the 8 coordinates of the four path waypoints and the 5 speeds corresponding to the five path legs. Exact analytical expressions for these derivatives, which make up the gradient of the utility function, are at best cumbersome and slow to compute. Therefore, the decision was made to use numerical estimates of the derivatives instead.

Attention was then turned to selection of the gradient algorithm to be used. It is now generally accepted that the so-called quasi-Newton or variable-metric approach to optimization is the most efficient on general non-linear functions; it is superior to non-gradient approaches even when the gradient must be estimated (Ref. 5). This approach uses an iteratively improved approximation H to the inverse matrix of second derivatives, instead of the true inverse used in Newton's method. A sequence of points converging to a local maximum is chosen by alternately searching in the direction of $H\underline{g}$ from the current point $\underline{x}$, where $\underline{g}$ is the gradient of the utility criterion function, until an approximate maximum is found in that direction, and then updating the matrix H. The method chosen for updating H is called the Broyden-Fletcher-Goldfarb-Shanno, or BFGS, update. This seems to be the best update formula available (Ref. 6). The update rule in vector notation is:

$$H^{+} = \left(I - \frac{sy^T}{y^Ts} \right) H \left(I - \frac{ys^T}{y^Ts} \right) + \frac{ss^T}{y^Ts} \qquad (1)$$

where

I = identity matrix

$s = \underline{x}^{+} - \underline{x}$

$y = \underline{g}^{+} - \underline{g}$

and where a plus (+) is used to denote the current minimization cycle as opposed to the previous cycle (denoted by lack of a plus).

The method used to perform the one-dimensional searches along $H\underline{g}$ is due to Shanno and his associates and is contained in a BFGS-update quasi-Newton algorithm called MINI published by Shanno and Phua in 1976 (Ref. 7). With minor modifications, MINI was the algorithm used for this study. The modification to accept forward difference approximations for the derivatives was chosen from a 1977 study of such approximations in optimization (Ref. 8).

Certain parameters of MINI were fixed throughout this study. Mode 2 of the MINI line search was used, since this is recommended by Reference 7 except when the matrix of second derivatives is singular. The maximum step length was set to 300 for each of the independent variables. Two optimization parameters were varied in the study to determine their effect on performance. These were the convergence criterion EPS and the relative step size parameter DFAC (used in the derivative approximation).

In addition to the change in the optimization algorithm, one other modification was made to the automated routine used in the previous study. This involved replacing the integration subroutine for probability of detection, which previously used a fixed number of points per leg, with a subroutine which adapts the number of points chosen to the accuracy specified (Task 6 of Ref. 9). The new integration subroutine is a modified Havie algorithm (Ref. 7) with maximum order of extrapolation set to 8. The relative accuracy parameter ACC was varied in this study, along with the parameters EPS and DFAC mentioned above.

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